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Verification of an experimental prediction method for railway induced vibration

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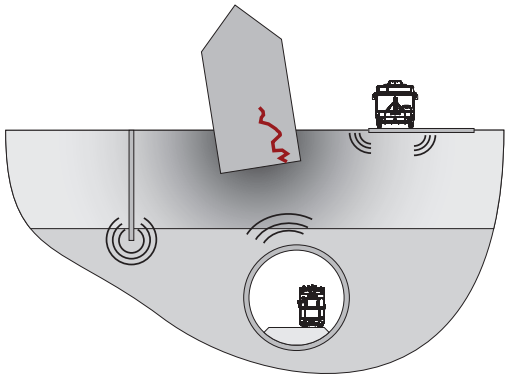
Railway induced vibrations and re-radiated noise in buildings

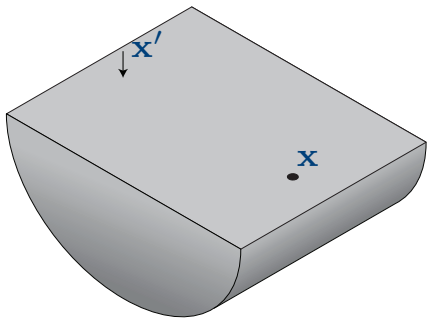


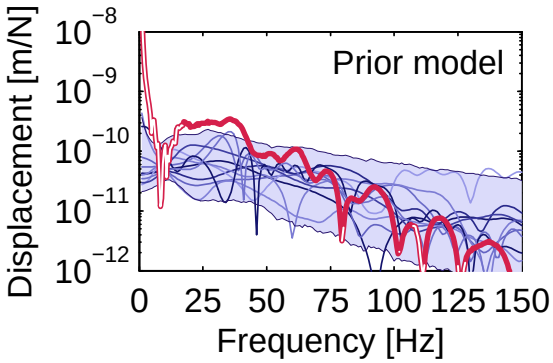
- Excitation mechanisms: wheel/rail roughness, rail joints,...
- Vehicle-track interaction: dynamic axle loads.
- Dynamic interaction between the tunnel and the soil: transfer functions.
- Wave propagation in the soil: dynamic reciprocity theorem.
- Dynamic soil-structure interaction.
- Vibrations in buildings (1 to 80 Hz).
- Re-radiated noise in buildings (16 to 250 Hz).

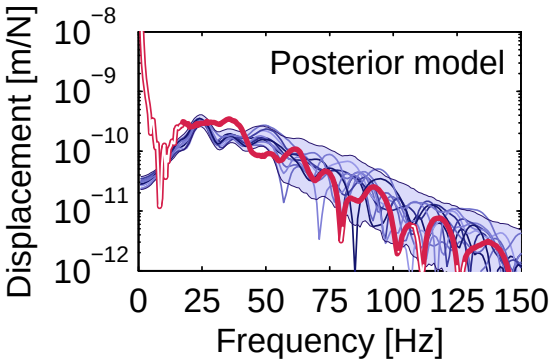
Prediction methods

- Numerical predictions [Lombaert et al., JSV, 2009][François et al., CMAME, 2010]
  - \+ Great variety in numerical models
  - – Need for accurate parameter characterization
- Empirical predictions
  - \+ Soil characteristics inherently taken into account
  - – Accurate input data is not always available
- Hybrid predictions

- Experimental transfer function (red) and 95% confidence region (blue) between 2 points in the free field [Schevenels, OPTEC, 2009]

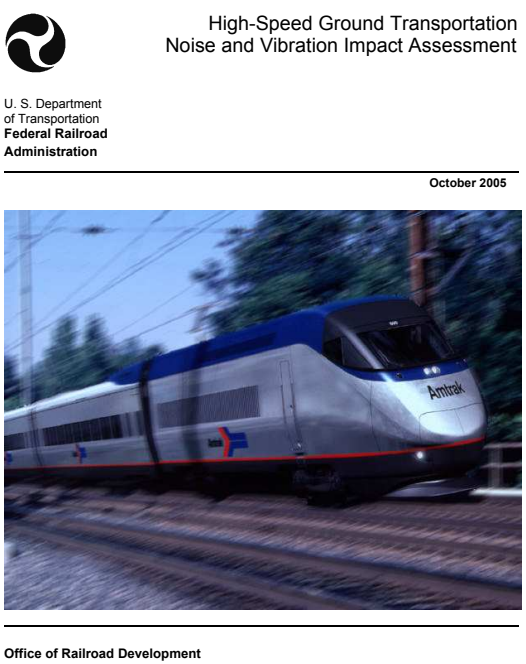


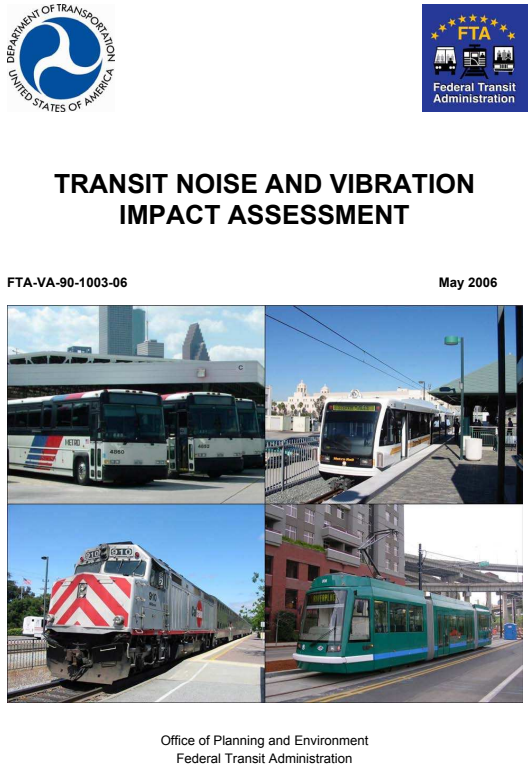




FRA procedure

- Detailed Vibration Assessment
  - Federal Railroad Administration (FRA) and Federal Transit Administration (FTA) [Hanson et al., FRA, 2005; Hanson et al., FTA, 2006]



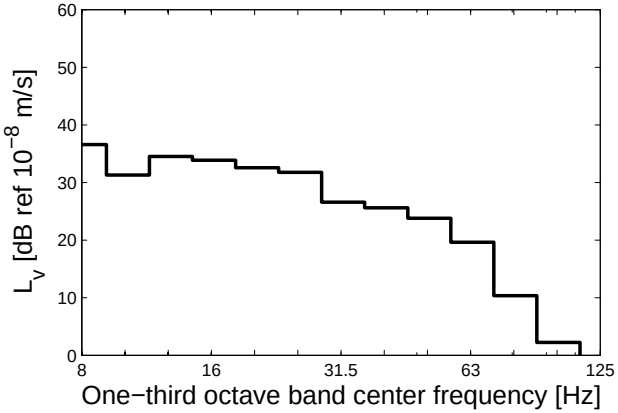


Vibration velocity level

- Prediction of the ground vibration velocity level in one-third octave bands [Hanson et al., 2005, 2006]

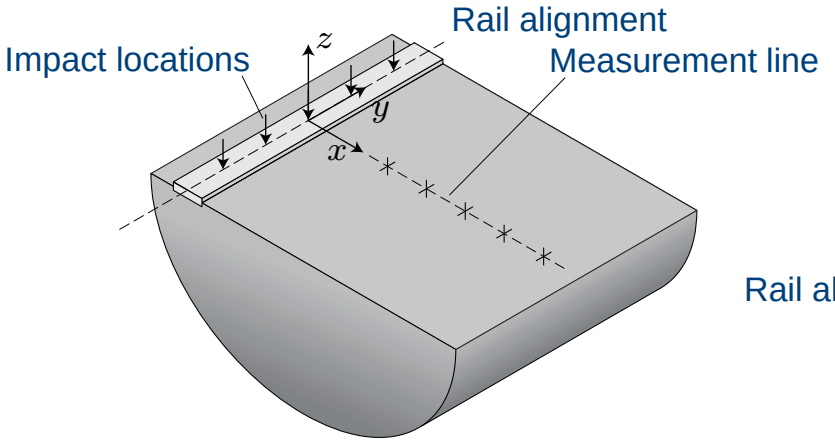
$$\mathrm{L_v} = \mathrm{L_F} + \mathrm{TM_L} \tag{1}$$

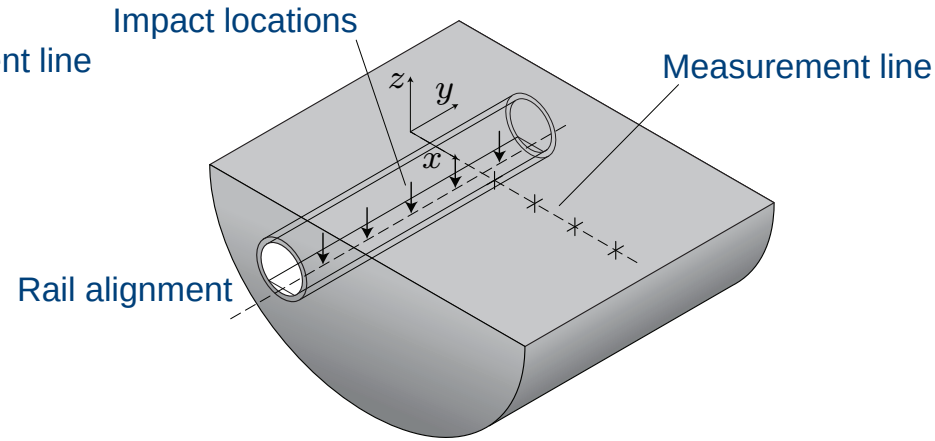
  - Vibration velocity level $\mathrm{L_v} = 20\log_{10}(v_{\mathrm{RMS}})$ [dB ref 10^{-8} m/s]
  - Force density $\mathrm{L_F}$ [dB ref $\mathrm{N}/\sqrt{\mathrm{m}}$]
  - Line transfer mobility $\mathrm{TM_L}$ [dB ref $10^{-8}\,\frac{\mathrm{m/s}}{\mathrm{N}/\sqrt{\mathrm{m}}}$]

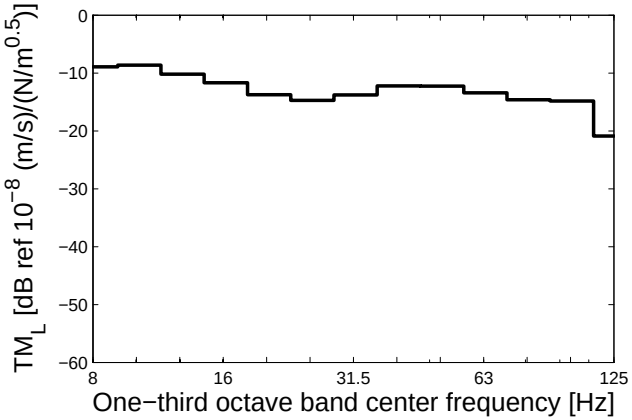


Line transfer mobility $\mathrm{TM_L}$

- Characterization of the transfer of vibration $\mathrm{TM_L} = 10\log_{10}\left(h\sum_{k=1}^{n} 10^{\frac{\mathrm{TM_{P}}k}{10}}\right)$



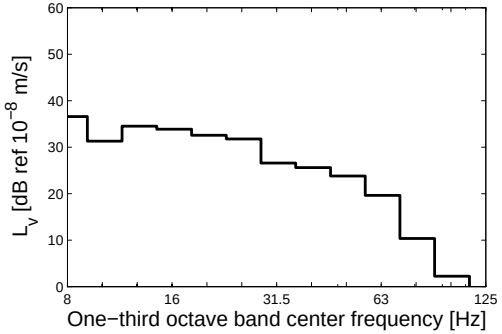




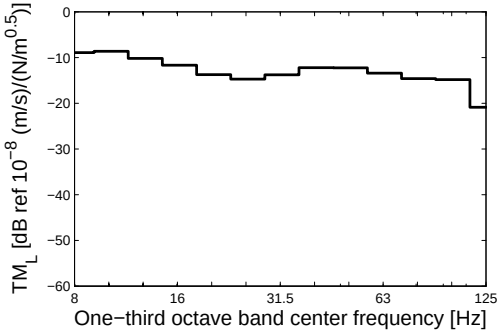
The FRA procedure

Force density $\mathrm{L_F}$

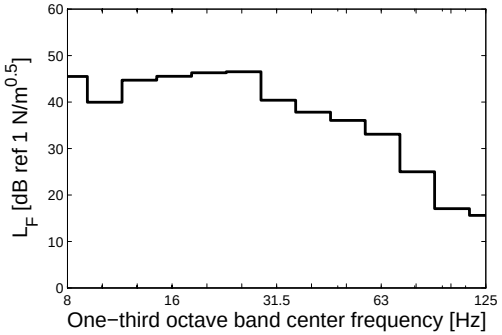
Vibration velocity level $\mathrm{L_v}$



Transfer mobility $\mathrm{TM_L}$



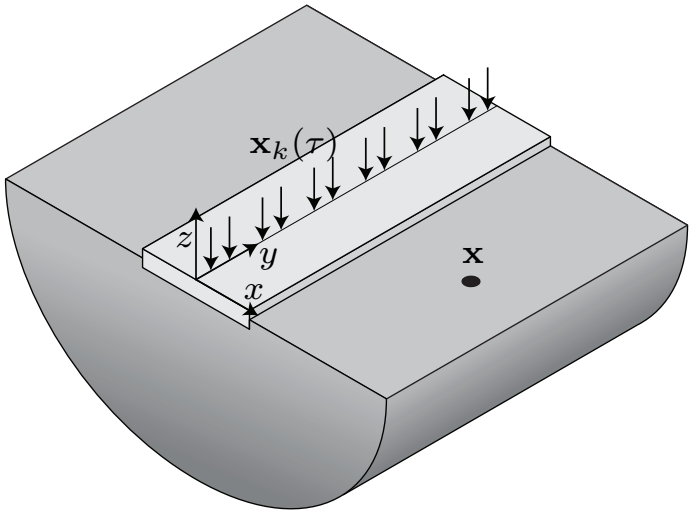
Force density $\mathrm{L_F} = \mathrm{L_v} - \mathrm{TM_L}$

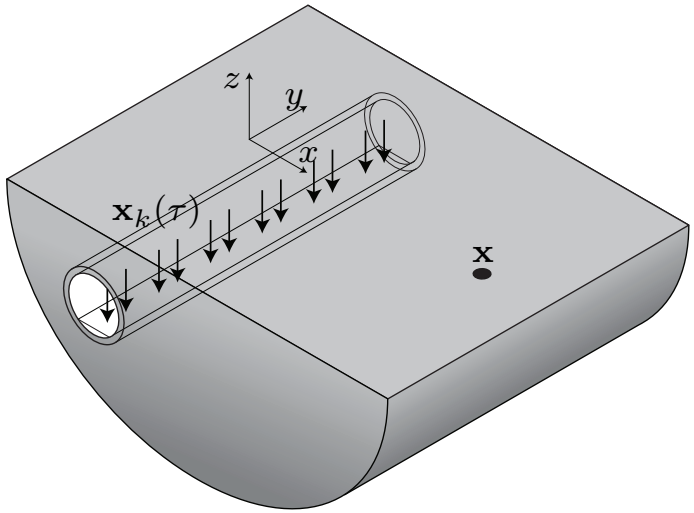


Moving dynamic loads

- Analytical expressions for the vibration velocity level due to moving loads in a tunnel or at grade [Sheng et al., 1999; Lombaert et al., 2000; Forrest and Hunt, 2006].

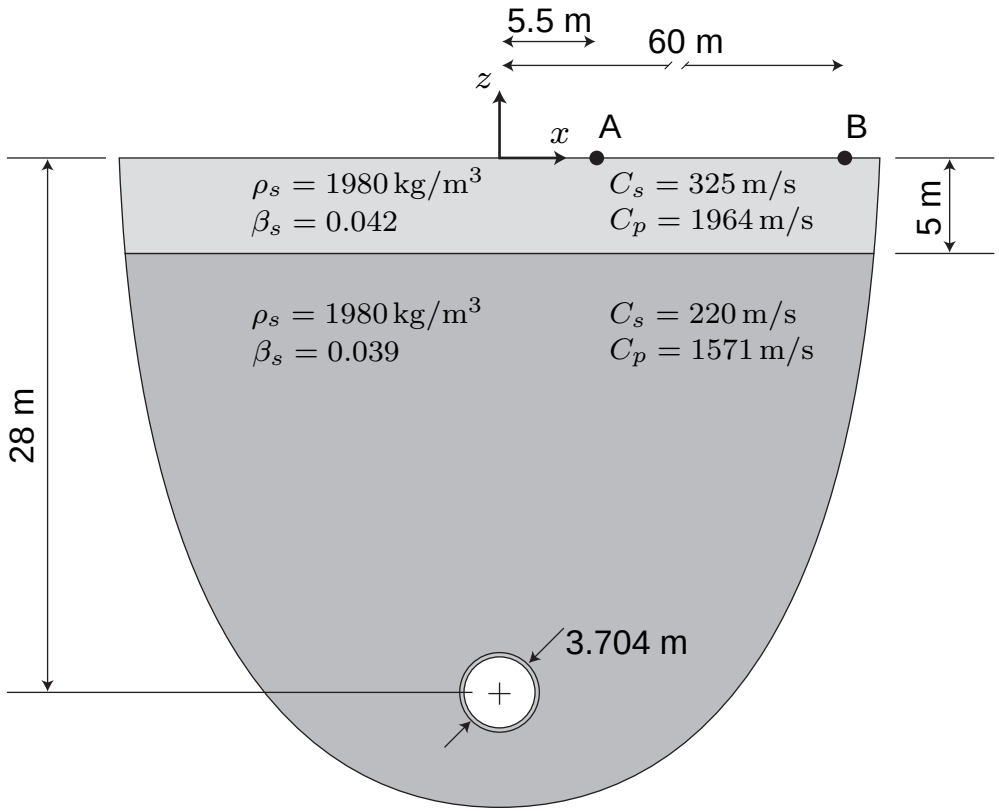
$$\mathbf{v}(\mathbf{x},t) = \sum_{k=1}^{n_\mathrm{a}} \int_{-\infty}^{t} \mathbf{H}^\mathrm{T}(\mathbf{x}_k(\tau),\mathbf{x},t-\tau)\mathbf{g}_k(\tau)d\tau \qquad (2)$$





Case

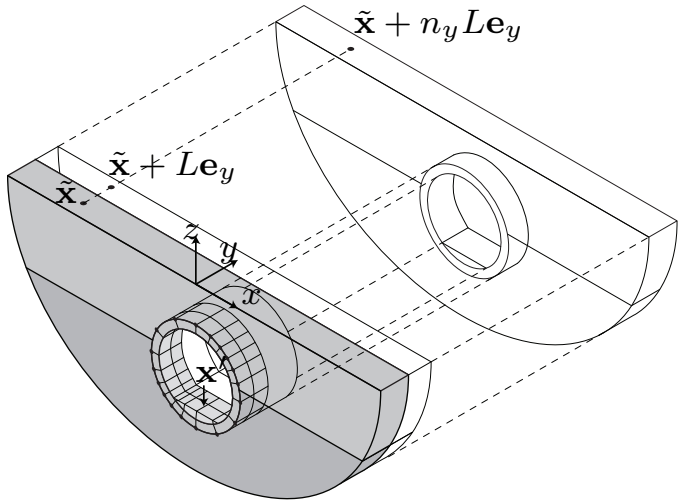
- Bakerloo line tunnel [Gupta et al., JSV, 2009]



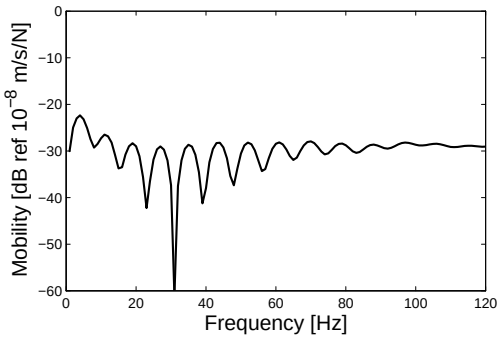
- Non-ballasted concrete slab track
- Train with 28 axles ($L_\mathrm{t} = 108.33\,\mathrm{m}$)
- Unevenness FRA class 3

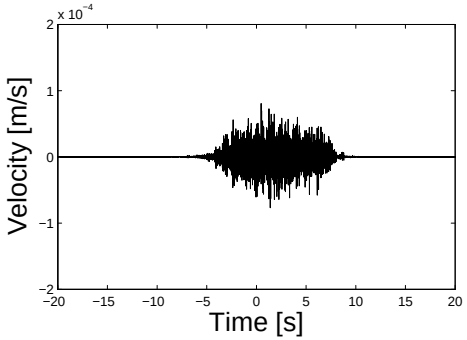
Numerical prediction: coupled periodic FE–BE model

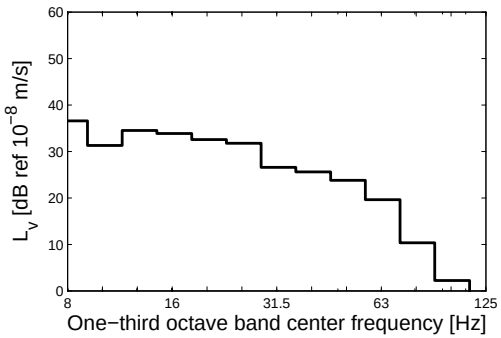
- Model [Degrande et al., JSV, 2006]



- (a) Transfer function, (b) time history and (c) one-third octave band spectrum of the vibration velocity in the free field in point A [Gupta et al., JSV, 2009]

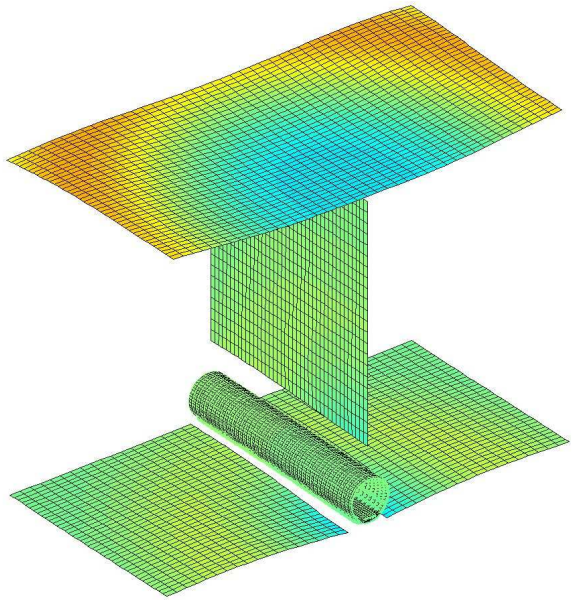




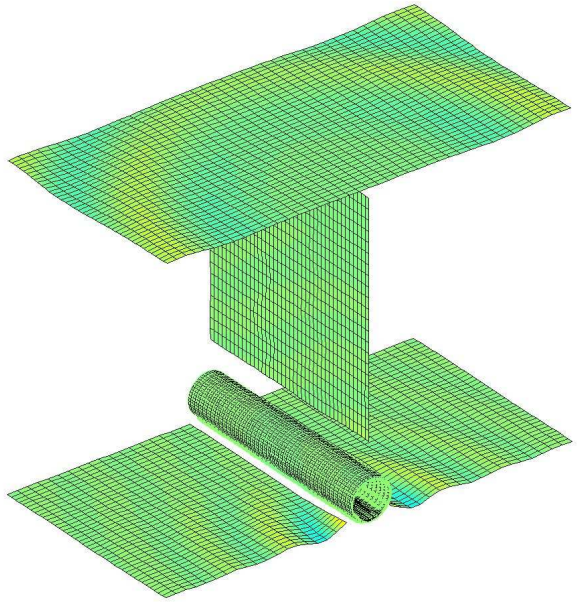


Numerical prediction model

- Transfer functions of the track-tunnel-soil system at (a) 10 Hz and (b) 40 Hz [Gupta, 2008]



(a)
Animation (avi) and zoom (avi).



(b)
Animation (avi) and zoom (avi).

- Response (avi) in the free field due to a carriage moving at constant speed on an uneven rail with a single wavelength unevenness (excitation at 40 Hz).

Derivation of analytical expressions for $\mathrm{L_F}$ and $\mathrm{TM_L}$

- Vibration velocity

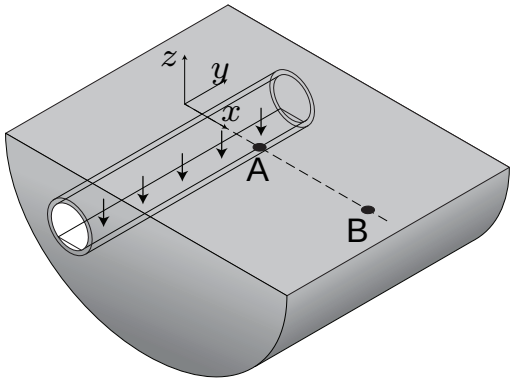
$$\mathbf{v}(\mathbf{x},t) = \sum_{k=1}^{n_\mathrm{a}} \int_{-\infty}^{t} \mathbf{H}^\mathrm{T}(\mathbf{x}_k(\tau),\mathbf{x},t-\tau)\mathbf{g}_k(\tau)d\tau \tag{3}$$

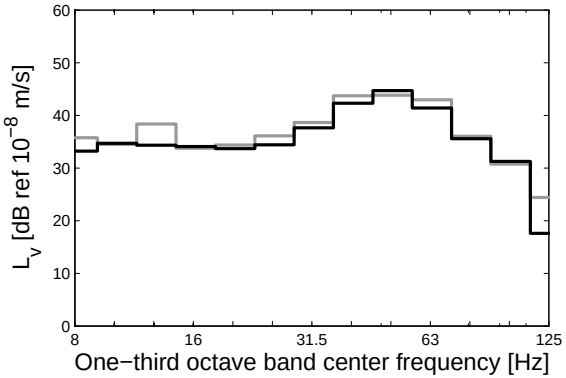
- Assumptions
  - Fixed point loads
  - Non-coherent and equal axle loads
  - Frequency-averaged transfer function
  - Equidistant point sources
- Analytical expressions for $\mathrm{L_F}$ and $\mathrm{TM_L}$

$$\mathrm{L_v} = \underbrace{10\log_{10}\left[\frac{g_\mathrm{RMS}^2}{L_\mathrm{a}}\right]}_{\mathrm{L_F}} + \underbrace{10\log_{10}\left[L_\mathrm{a}\sum_{k=1}^{n_\mathrm{a}}\frac{\int_{\omega_1}^{\omega_2}|\hat{h}_{zz}(\mathbf{x}_k,\mathbf{x},\omega)|^2 d\omega}{\Delta\omega}\right]}_{\mathrm{TM_L}} \tag{4}$$

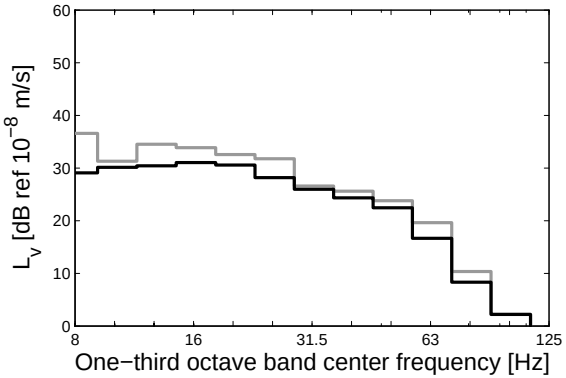
Results

- One-third octave band spectra of the velocity in (a) point A and (b) point B for a train passage at a speed of 30 km/h calculated with the numerical method (grey line) and the FRA procedure (black line).





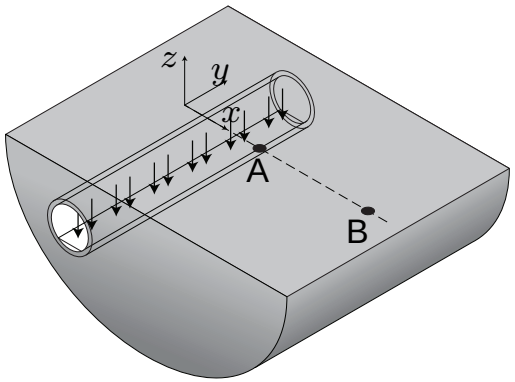
(a)

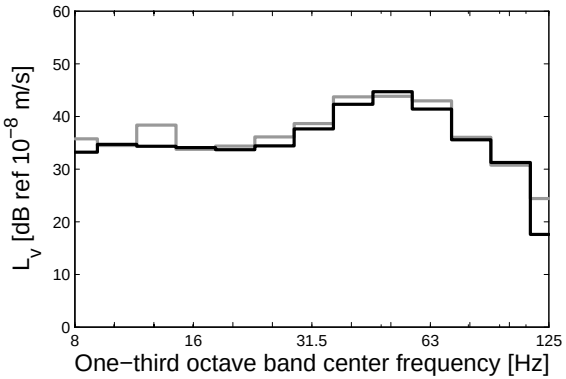


(b)

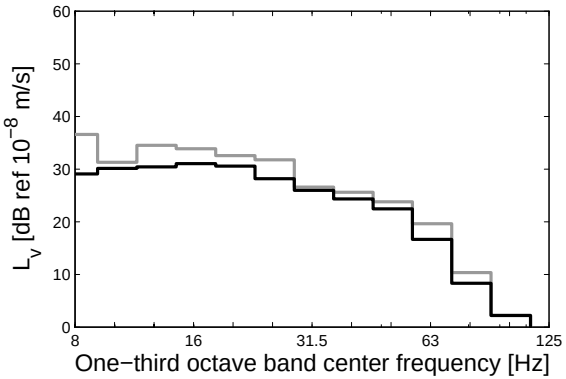
Assumption 1: fixed point loads

- One-thirds octave band RMS value of the vertical velocity in (a) point A and (b) point B due to a moving train (grey line) and due to a fixed train (black line).





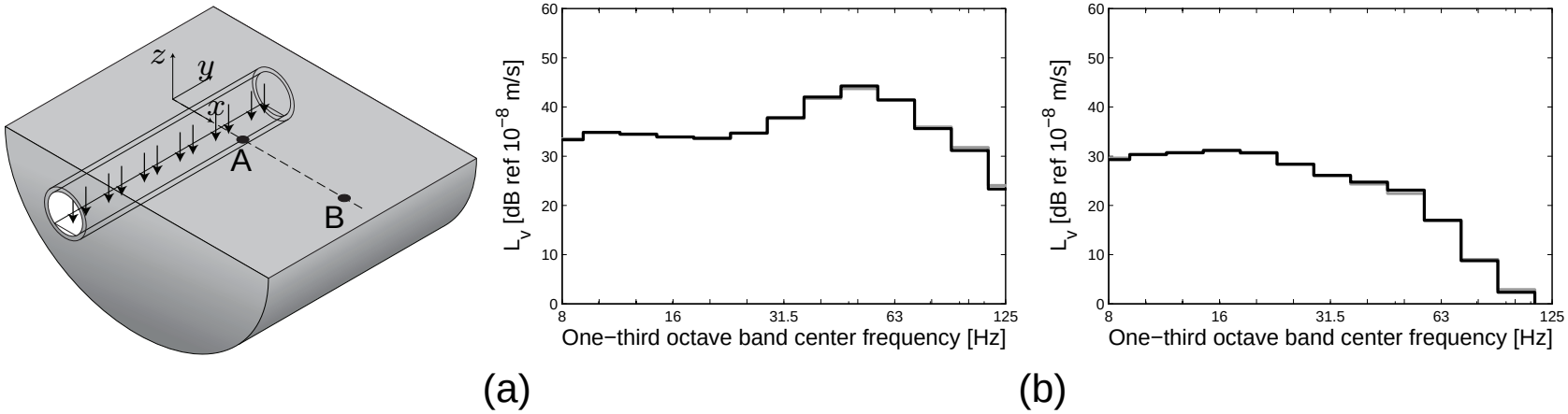
(a)



(b)

Assumption 2: non-coherent and equal axle loads

- One-third octave band RMS value of the vertical velocity in (a) point A and (b) point B with coherent point loads (grey line) and non-coherent point loads (black line)

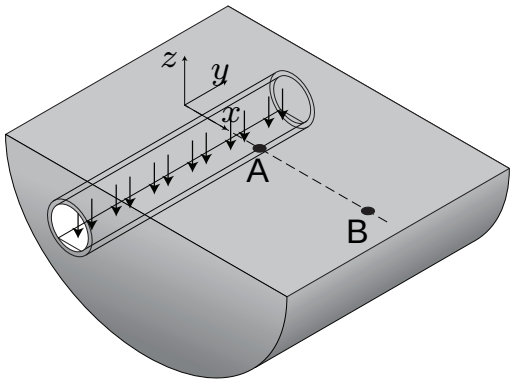


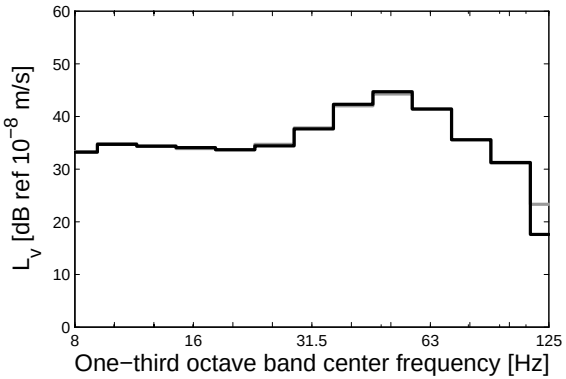
(a) (b)

[Hunt, 1996; Wu and Thompson, 2001]

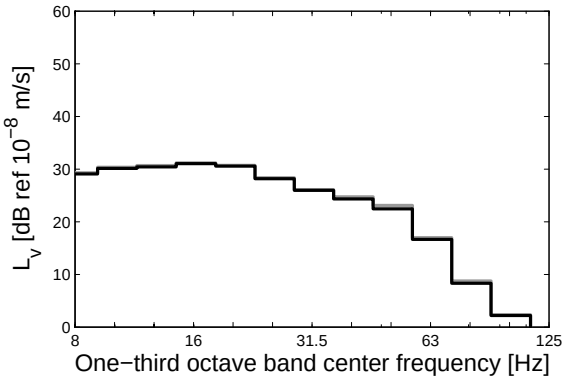
Assumption 3: average value of the transfer function

- One-third octave band spectra of the velocity in (a) point A and (b) point B with narrow band (grey line) and frequency-averaged (black line) transfer function.





(a)

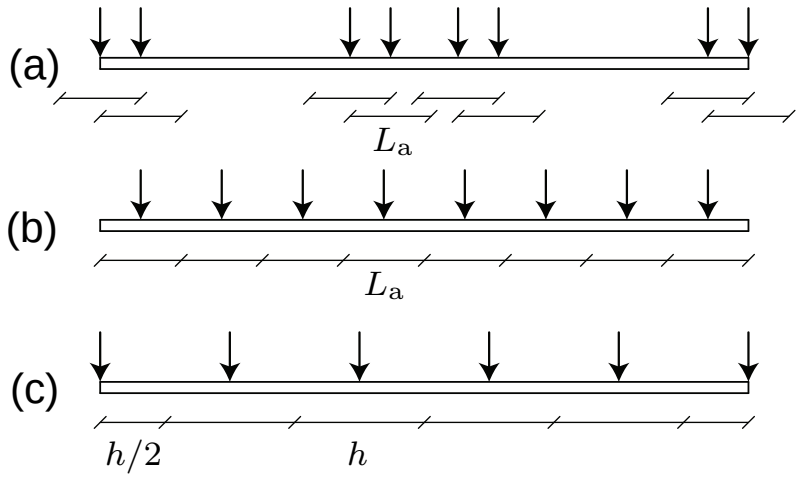


(b)

Assumption 4: equidistant point sources

- Transfer mobility

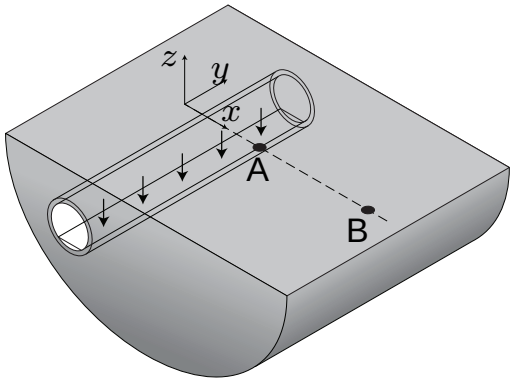
$$\mathrm{TM_L} = 10\log_{10}\left(L_\mathrm{a}\sum_{k=1}^{n_\mathrm{a}}\frac{\int_{\omega_1}^{\omega_2}|\hat{h}_{zz}(\mathbf{x}_k,\mathbf{x},\omega)|^2 d\omega}{\Delta\omega}\right) \quad (5)$$

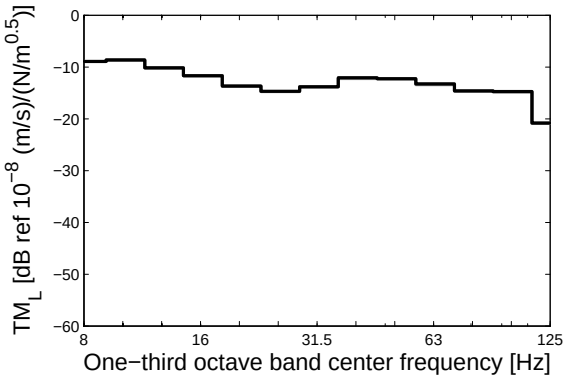


$$\mathrm{TM_L} = 10\log_{10}\left(h\sum_{k=1}^{n}10^{\frac{\mathrm{TM_P}k}{10}}\right) \quad (6)$$

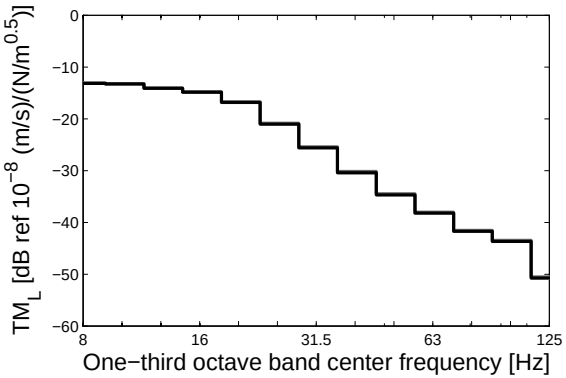
Assumption 4: equidistant point sources

- Transfer mobility in (a) point A and (b) point B calculated with the original axle positions (light-grey line), with 28 equidistant axle positions (dark-grey line) and with 15 equidistant axle positions including two edge points (black line).





(a)



(b)

Conclusion

- Separate characterization of force density and line transfer mobility leads to a good approximation of the one-third octave band vibration velocity level
- Analytical expressions of force density and line transfer mobility are obtained based on four assumptions
  - Fixed train position
  - Non-coherent axle loads
  - Averaged transfer function
  - Equidistant point loads
- The results for tunnels are also validated for the case of railway traffic at grade